

Macrophyte Research Strategy

Research priorities for creating a coral reef macrophytes index of biological integrity are outlined in Table 13. Macrophytes in tropical marine waters may be comprised of vascular plants (e.g., seagrasses) and algae (e.g., sessile and drift). Macrophytes are a vital resource because of their value as extensive primary producers; a food source; a habitat and nursery area for commercially and recreationally important fish species; as a protection against shoreline erosion; and as a buffering mechanism for excessive nutrient loadings. Because of the combined high productivity and habitat function of the plant assemblage, any or all of the other coral reef biota can be affected by the presence or absence of macrophytes.

Some of the advantages of using marine macrophytes in biological surveys are as follows (Gibson et al., 1997).

- Vascular plants are a sessile assemblage. There is essentially no mobility to rooted vascular or holdfast-established algal plant communities, so expansion or contraction of seagrass beds can be readily measured as an environmental indicator.
- Sampling frequency is reduced because of the relatively low assemblage turnover relative to other biota such as benthic invertebrates or fish.
- Taxonomic identification in a given area is cumulatively consistent and straight forward.

Some of the disadvantages of macrophyte surveys are as follows (Gibson et al., 1997).

- Relatively slow response by the plant assemblage to perturbation makes this a delayed indicator of water quality impacts. This could be critical if prompt management responses are needed.
- Successional blooms of some macrophytes means seasonal cycles need to be identified and accommodated by the survey schedule to avoid misinterpretation of data and false assumptions of water quality impacts.
- Changes in abundance and extent of submerged macrophytes are not necessarily related to changes in water quality.

Table 13. Research priorities for creating a coral reef macrophytes index of biological integrity. Percent sign (%) denotes relative abundance (number of individuals of one taxa as compared to that of the whole assemblage). Cumulative = cumulative human-induced disturbance (i.e., a combination of factors that could include (but is not limited to) fishing, increased temperature and turbidity, chemical contaminants, sedimentation, altered flow regimes, pesticides, nutrients, metals, sediments, and/or bacteria. To reach metric status attributes need the following research: 1 = a quantitative dose-response change in attribute value documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation; 2 = calibration for specific region/location; 3 = transformation. In addition, the entire IBI needs index development (an interpretive framework) that will result in the calculation of a simple numerical score for a particular site, which can then be compared over time or with other similar sites. Attributes can be applied to all tropical seas.

Organizing Structure	Hypothetical Response Specificity	Hypothetical Response	Research Needs
Attributes			
Community & Assemblage Structure			
Taxa richness			
Total taxa richness (number of taxa/sample)	Cumulative	Decrease	1, 2, 3
Percent cover	Nutrients	Increase	1, 2, 3
Dominance			
% dominant taxa	Nutrients	Increase	1, 2, 3
Taxonomic Condition			
Sensitivity (tolerants and intolerants)			
Number of sediment-intolerant taxa ¹	Sediment	Decrease	1, 2, 3
% sediment-tolerant taxa ²	Sediment	Increase	1, 2, 3
Individual condition			
Contaminant levels			
Plant tissue nitrogen isotope ratios	Fecal waste	Increase	1, 2, 3
Biological Processes			

Productivity			
Primary productivity (Pmax)	Nutrients	Increase	1, 2, 3
C:N:P content of algae	Nutrients	Increase	1, 2, 3
Alkaline phosphatase assay	Nutrients	Increase	1, 2, 3

¹ Potential candidates include: to be determined

² Potential candidates in the Indo-Pacific include: the blue-green *Lyngbya majuscula*, and three red algae *Tolypiocladia glomerulata*, *Amansia glomerata* and the articulate coralline *Jania sp* (R. T. Tsuda, University of Guam, pers. comm.).

Phytoplankton Research Strategy

Research priorities for creating a coral reef phytoplankton index of biological integrity are outlined in Table 14.

The advantages of using phytoplankton include the following (Gibson et al., 1997).

- Phytoplankton provide a notable indication of nutrient enrichment in marine environments (as do other attributes). Changes in nutrient concentrations can result in long-term changes in assemblage structure and function and planktonic primary producers are one of the earliest assemblages to respond.
- Changes in phytoplankton primary production will in turn affect higher trophic levels of macroinvertebrates and fish.
- Many governments routinely monitor [chlorophyll a] as part of water quality monitoring due to the ease and relatively low cost of analysis.
- Phytoplankton have cumulatively short life cycles and rapid reproduction rates making them valuable indicators of short-term impact.

The disadvantages associated with using phytoplankton include the following (Gibson et al., 1997).

- The fact that phytoplankton are subject to rapid distribution with the winds, tides, and currents means they may not remain in place long enough to be source identifiers of short-term impacts. This problem is compounded by the ability of some phytoplankton to synthesize atmospheric sources of nitrogen, thus confounding the identification of runoff sources of nutrients and the resultant changes in the coral reef biota.
- Taxonomic identification of phytoplankton can be difficult and time-consuming.
- Competition by macrophytes, higher respiration rates, and increased grazing by zooplankton may counteract increased phytoplankton biomass resulting from nutrient enrichment. These reasons argue for investigating phytoplankton and zooplankton together as biological indicators.
- Phytoplankton can undergo blooms, the causes of which might be indeterminate, at varying frequencies.

Table 14. Research priorities for creating a coral reef phytoplankton index of biological integrity. Percent sign (%) denotes relative abundance (number of individuals of one taxa as compared to that of the whole assemblage). Cumulative = cumulative human-induced disturbance (i.e., a combination of factors that could include (but is not limited to) fishing, increased temperature and turbidity, chemical contaminants, sedimentation, altered flow regimes, pesticides, nutrients, metals, sediments, and/or bacteria. To reach metric status attributes need the following research: 1 = a quantitative dose-response change in attribute value documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation; 2 = calibration for specific region/location; 3 = transformation. In addition, the entire IBI needs index development (an interpretive framework) that will result in the calculation of a simple numerical score for a particular site, which can then be compared over time or with other similar sites. Attributes can be applied to all tropical seas.

Organizing Structure	Hypothetical Response Specificity	Hypothetical Response	Research Needs
Community & Assemblage Structure			
Taxa richness			
Total taxa richness (number of taxa/sample)	Cumulative	Decrease	1, 2, 3
Dominance			
% dominant taxa	Nutrients	Increase	1, 2, 3
Taxonomic Condition			
Sensitivity (tolerants and intolerants)			
Number of intolerant taxa ¹	Cumulative	Decrease	1, 2, 3
% tolerant taxa ²	Cumulative	Increase	1, 2, 3
Biological Processes			
Productivity			
Phytoplankton [chlorophyll a]	Nutrients	Increase	1, 2, 3
Cyanobacterial blooms	Nutrients	Increase	1, 2, 3

^{1, 2} To be determined

Zooplankton Research Strategy

Research priorities for creating a coral reef zooplankton index of biological integrity are outlined in Table 15. Zooplankton consist of two basic categories: holoplankton which spend their entire life cycle as plankton, and meroplankton which are only plankton while in the larval life stage. Holoplankton are characterized by rapid growth rates, broad physiological tolerance ranges, and behavioral patterns which promote their survival in marine waters. The calanoid copepods are the numerically dominant group of the holoplankton, and the genus *Acartia* (*A. tonsa* and *A. clausi*) is the most abundant and widespread. *Acartia* is able to withstand fresh to hypersaline waters and temperatures ranging from 0° to 40° C. The meroplankton are much more diverse than the holoplankton and consist of the larvae of polychaetes, barnacles, mollusks, bryozoans, echinoderms, and tunicates as well as the eggs, larvae, and young of crustaceans and fish. Zooplankton populations are subject to extensive seasonal fluctuations reflecting hydrologic processes, recruitment, food sources, temperature, and predation. They are of considerable importance as the link between planktonic primary producers and higher carnivores. As such, they are also early indicators of trophic shifts in the aquatic system (Gibson et al., 1997).

Advantages of zooplankton sampling are similar to phytoplankton and include the following (Gibson et al., 1997).

- The rapid turnover of the assemblage provides a quick response indicator to water quality perturbation. The challenge will be to sort out the rapid turnover due to human influences from the rapid and normal seasonal turnover in species composition and abundances.
- Sampling equipment is inexpensive and easily used.
- Compared to phytoplankton, sorting and identification is fairly easy.

Some limitations of using zooplankton in biosurveys include the following (Gibson et al., 1997).

- The lack of a substantial data base for most regions.
- The high mobility and turnover rate of zooplankton in the water column. While this permits a quick response by zooplankton to environmental changes on the one hand, it also increases the difficulty of evaluating cause and effect relationships for this assemblage.

Table 15. Research priorities for creating a coral reef zooplankton index of biological integrity. Percent sign (%) denotes relative abundance (number of individuals of one taxa as compared to that of the whole assemblage). Cumulative = cumulative human-induced disturbance (i.e., a combination of factors that could include (but is not limited to) fishing, increased temperature and turbidity, chemical contaminants, sedimentation, altered flow regimes, pesticides, nutrients, metals, sediments, and/or bacteria. To reach metric status attributes need the following research: 1 = a quantitative dose-response change in attribute value documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation; 2 = calibration for specific region/location; 3 = transformation. In addition, the entire IBI needs index development (an interpretive framework) that will result in the calculation of a simple numerical score for a particular site, which can then be compared over time or with other similar sites. Attributes can be applied to all tropical seas.

Organizing Structure Attributes	Hypothetical Response Specificity	Hypothetical Response	Research Needs
Community & Assemblage Structure			
Taxa richness			
Total number of larval fish families	Cumulative	Decrease	1, 2, 3
Dominance			
% dominant larval fish family	Cumulative	Increase	1, 2, 3
Taxonomic Composition			
Sensitivity (tolerants and intolerants)			
Larval fish and other reef taxa families ¹	Cumulative	Decrease	1, 2, 3
Individual condition			
Anomalies			
% deformity in larval fish	Cumulative	Increase	1, 2, 3
Contaminant levels			
Coral egg-sperm interactions	Cumulative	Decrease	1, 2, 3
Coral embryological development	Cumulative	Decrease	1, 2, 3
Coral larval settlement & metamorphosis	Cumulative	Decrease	1, 2, 3
Coral acquisition of zooxanthellae	Cumulative	Decrease	1, 2, 3

¹ To be determined

Using IBIs to Diagnose Causes of Biological Degradation

In previous papers, we have suggested that useful coral reef metrics within an IBI should show response specificity; that is, a response which is indicative of a relatively small number or numerous stressors (Jameson et al., 1998; Erdmann and Caldwell, 1997). A coral reef IBI containing a suite of metrics with varying levels of specificity would insure that known as well as unknown human stressors are detected. Such response specificity would obviously be useful in allowing reef managers to pinpoint the cause(s) of change on their reefs in order that management actions can be taken to ameliorate the perceived stress. Typical human reef stressors can be categorized hierarchically; physical stress (e.g., blast fishing, coral mining, anchor and diver damage), water quality degradation/eutrophication stress *sensu* Tomascik and Sander (1987a & b; i.e., a combination of nutrient enhancement, increased sedimentation, and introduction of marine toxins), biological infestations (e.g., coral diseases), and even ecosystem shifts due to overfishing. At the more proximal level, it is possible to differentiate specific stresses such as heavy metal pollution, or even more specifically, mercury (Hg) pollution. At what level can we reasonably expect a coral reef IBI to differentiate between stressors?

Even at this relatively early stage of reef biomonitoring, it is certainly possible to use currently-accepted coral reef attributes to differentiate between broad categories of reef stressors. As an example, a recent study in the Pulau Seribu Archipelago in Indonesia revealed a drastic reduction in the percentage of live coral cover on a number of reefs during the ten-year period between UNESCO-sponsored surveys (Brown, 1986; Soemodihardjo, 1999). Early speculation as to the cause of the degradation by the coral ecologists in the survey team centered upon *Acanthaster plancii* infestation, but a strongly pronounced size-class truncation of reef-flat stomatopod assemblages on the same reefs suggested that the cause was more likely a “pulse” disturbance in 1991-1992, probably El Niño-related heat stress (Erdmann and Sisovann, 1999). In this case, the inclusion of stomatopods in the reef monitoring protocol enabled researchers to differentiate between reef degradation due to biological infestations versus that due to a short-term physical stress.

At the more proximal level, few coral reef attributes seem able to differentiate specific stressors, such as mercury pollution versus petroleum hydrocarbon pollution. This fact reinforces the importance of collecting ancillary information on human activity and influences to aid in the interpretation of the biological signal (just as the doctor wants to know things about a person's lifestyle as well as the metabolic and physiological measures of their health).

Examples of those indicator organisms which are extremely response specific include the gastropod imposex response to tributyl tin contamination (Ellis and Pattisina, 1990), changes in foraminiferal assemblages from algal symbiont-bearing taxa to heterotrophic taxa in response to nutrient enhancement (Cockey et al., 1996), changes in the size, density, and starch sheath of zooxanthellae in giant clams in response to nutrient enhancement (Ambariyanto and Hoegh-Guldberg, 1996; Belda-Baillie et al., 1998), and developmental defects in reef fishes as a result of PCB or dioxin contamination (Lisa Kerr, University of Maryland, Baltimore, USA, pers. comm.).

However, many other proposed coral reef indicator organisms are considerably less specific in their response, particularly with regard to water quality degradation. As an example, stomatopod abundance, diversity and recruitment are reduced by a variety of marine pollutants, including petroleum hydrocarbons (Steger and Caldwell, 1993), heavy metals (Erdmann and Caldwell, 1997), domestic sewage (Erdmann, 1997; Gajbhiye et al., 1987) and ammonium and phosphate enrichment (ENCORE team, in review). Other promising indicator organisms of water quality deterioration, such as rubble-boring sponges (Holmes, 1997; Holmes et al., 2000) and amphipods (Thomas, 1993), are also sensitive to a range of eutrophication/marine pollution agents.

The issue of response specificity is also of concern in the more developed field of freshwater monitoring (discussed in Johnson et al., 1993; Davis and Simon, 1995; Simon, 1998; Karr and Chu, 1999). Unfortunately, it seems that even freshwater indicator organisms rarely provide such an easily measured, stressor-specific response as gastropod imposex in response to tributyl tin contamination. In freshwater monitoring, the issue of response specificity has been examined primarily at the suborganismal level; for example, changes in enzymatic activity of clams in response to Cu and Zn in power plant effluents (Farris et al., 1988) and changes in hemolymph ion regulation in midges exposed to naphthalene (Darville et al., 1983). Freshwater monitoring has also made extensive use of bioaccumulating indicators, or sentinel organisms, which actually accumulate specific toxins in their tissues (Johnson et al., 1993). While such techniques are preferable to direct chemical analysis of receiving waters in that they assess only those pollutants which are bioavailable and ecologically relevant, they nonetheless require detailed chemical analyses.

We will never have screens for all the thousands of compounds that degrade marine water quality - and if we did we would be neglecting the other 4 major factors listed in Table 2. We can and must work on the most important response specific screens and use general screens to find the others (rather than working on all the individual compounds first).

In general, the coral reef attributes listed in Tables 10-15 and in Jameson et al. (1998) are often able to differentiate between broad categories of stressors, but with a few notable exceptions, do not show specific responses to individual stressors (particularly those involved in water quality degradation). With further research, it may become possible to develop a multimetric index that includes a range of attributes with unique responses to a wide variety of possible stressors. Several workers have argued that it is ecologically unrealistic to attempt to monitor such stresses as nutrient enhancement and introduction of marine toxins in isolation, as they almost invariably occur together, and likely with additive or synergistic effects (Tomascik and Sander, 1987a; Smith et al., 1988; Karr and Chu, 1999).

Given these considerations, a “best course of action” for the future of coral reef assessment may include development of multimetric indexes that address the five attributes of coral reef resources that are altered by cumulative effects of human activity (Table 2) and that use the framework outlined in Figure 1 for basic reference. Indexes should include a taxonomically-diverse group of indicator organisms that show a unique response to several different broad categories of stressors,

as well as a select few organisms which are able to detect specific stresses of particular concern to individual monitoring programs (Tables 10-15). For example, a “generic” multimetric index of broad applicability for pilot monitoring studies in most coral reef ecoregions might include metrics based on a variety of pollution-sensitive coral rubble cryptofauna (e.g., boring sponges, stomatopods and/or amphipods), specific bioindicators of nutrient enhancement (e.g., giant clam zooxanthellae, foraminifera, nitrogen isotope techniques), indicators of fishing (e.g., monitoring of reef food-fish relative abundance), and several of the more commonly used parameters of hard coral “health” (e.g., colony size structure, mortality index, coral damage index). In situations where stress is detected with the multimetric index, supplemental analyses of the factors listed in Table 2 may also be required to pinpoint the stressor(s) to the coral reef. Analysis of regional human activity in the adjacent terrestrial landscape will more likely be associated with changes in biological condition than a few narrow chemical parameters (J. R. Karr, personal observation). Indeed, Risk et al. (1994; in press) have argued that reef monitoring programs are most effectively designed as a combination of “low-tech” and “high-tech” science, with low-tech biomonitoring techniques used to detect ecologically-relevant stresses to the reef, followed by high-tech geochemical analytical techniques to determine the exact stressor(s).

Well designed coral reef IBIs have the potential to give a reliable early warning signal of general reef impairment. However, to diagnose what is actually causing the impairment requires focusing in on the raw data of the individual metrics within the IBI (especially the various response specific indicators such as the coral damage index for physical damage, nitrogen isotope ratios in tissue for sewage detection, bioaccumulation in molluscs and corals for metal detection, and gastropod imposex for tributyltin detection). Habitat characterization measurements that are collected as part of the IBI process will also be critical in diagnosing specific causes of degradation. These measurements include but are not limited to: coral reef area, geomorphometric classification, habitat type, watershed land use, population density, pollution discharges, algal cover, salinity, conductivity, dissolved oxygen, temperature, pH, turbidity, Secchi depth, nutrients, organics, metals, depth, sediment grain size, total volatile solids, total organic carbon, acid volatile sulfides, sediment reduction-oxidation potential, and sediment contamination.

An extremely important practice to maximize the utility of the information generated in the IBI process and to expedite decision-making, is to always retain the raw data. These files can be used to translate historical data sets into present indexes for temporal continuity, and even more importantly, they can provide an interpretation and potential diagnosis for management action when a particular site is being evaluated.

Because a multimetric index (IBI) is a single numeric value, critics charge that the information associated with the metrics is somehow lost in calculating the index itself (USEPA, 1985; Suter, 1993). Multimetric indexes condense, integrate, and summarize — they don't lose — information. They comprise the summed response signatures of individual metrics, which individually point to likely causes of degradation at different sites (Karr et al., 1986; Yoder, 1991; Yoder and Rankin, 1995b). Although a single number, the index, is used to rank the condition of sites within a region, details about each site — expressed in the values of the component metrics — are retained

(Simon and Lyons, 1995). It is straightforward to translate these numeric values into words describing the precise nature of each component in a multimetric evaluation. These descriptions, together with their numeric values, are available for making site-specific assessments, such as pinpointing sources of degradation (Yoder and Rankin, 1995a) or identifying which attributes of a biotic assemblage are affected by human activities (Karr and Chu, 1999)

Rigorously constructed multimetric indexes are robust measurement tools. Although their development and use can sometimes be derailed, the failure of a monitoring protocol to assess environmental condition accurately or to protect coral reefs usually stems from conceptual, sampling, or analytical pitfalls. Multimetric indexes can be combined with other tools for measuring the condition of ecological systems in ways that enhance or hinder their effectiveness. Like any tool, they can be misused. That multimetric indexes can be, and are, misused does not mean that the multimetric approach itself is useless (Karr and Chu, 1999).

For best results the following pitfalls should be avoided (Karr and Chu, 1999).

Conceptual

- Excessive dependence on theory
- Narrow conceptual framework
- Failure to account for a gradient of human influence
- Expectation of simple chemical (or other) correlations
- Poor definition or misuse of reference condition

Sampling

- Inadequate design
- Too many or too few data
- Misunderstanding of the sources of variability
- Failure to sample across a gradient of human influence
- Inappropriate use of probability-based sampling

Analytical

- Use of incompatible data sets

- Failure to keep track of sources of variability
- Failure to understand cumulative ecological dose-response curves
- Inattention to important signals, such as rare species
- Failure to test metrics

The primary strengths of multimetric index development and use include:

- it is a rational, consistent way to reduce large amounts of data to meaningful interpretations;
- it is a quantitative treatment of the observations which permits statistical assessments;
- interpretive bias is reduced in the treatment of the data; and
- it helps us to target components and gives context to the data that provides new understanding and better information for effective communication.

In closing, the IBI approach helps us to find more "information" in the data that we have collected and it gives us a formal framework to use that information, something that was not available in the past when many researchers simply collected "data" and produced uninspiring summaries of those data that were largely ignored by those working at the policy level.

Next Steps

To help to coordinate and guide future research, this paper and progress on implementing the coral reef IBI research strategy will be widely disseminated to the research community via the internet at the USEPA coral reef web site (<http://www.epa.gov/owow/oceans/coral>). Efforts will be made by U.S. government funding agencies to implement this research strategy for coral reefs under U.S. jurisdiction. Jameson et al., (in prep.) are in the process of designing a coral reef classification system for reefs under U. S. jurisdiction to determine reference conditions and regional ecological expectations (Step 1-Table 4). IBI 's will be tested and refined via pilot programs on U.S. coral reefs in the Caribbean and Pacific. Hopefully, other nations will join in this endeavor to fund and implement aspects of this research strategy.

Acknowledgements

This research was funded by the U.S. Environmental Protection Agency under contract (8W-0622-NASX) to Coral Seas Inc. - Integrated Coastal Zone Management. MVE would like to gratefully acknowledge the support of the U.S. National Science Foundation's International Research Fellows Program (No. INT-9704616). We thank two anonymous peer reviewers for constructive comments on the entire manuscript.